

Passage of the Year 2026

October 13th 2026

Cosmology with GWs and LSS tracers in view of next generation observatories



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In collaboration with:

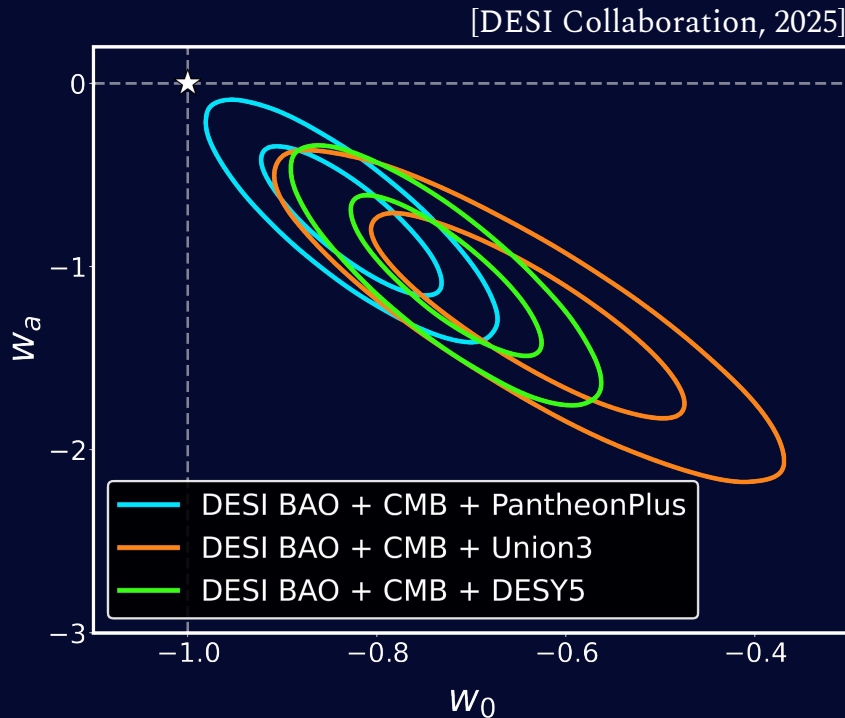
**Riccardo Murgia, Jan Harms, Andrea Cozzumbo, Ulyana Dupletsa,
Simone Mastrogiovanni, Tommaso Ronconi, Giona Sala, Marta Spinelli**

Current Cosmological Framework

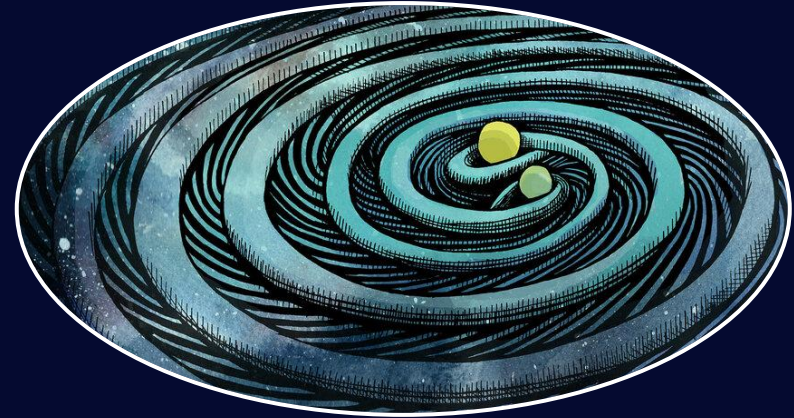
Λ CDM incredibly successful

Dark sector remains unknown:
discrepancies remain unsolved

Test alternative well-motivated
models to restore cosmological
concordance.



Using gravitational waves as standard sirens



Standard Sirens

$$d_L = a(t_0)(1 + z) \int_0^z \frac{cdz'}{a(t_0)H(z')}$$

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Bright Sirens

The sources of GW events emit also some electromagnetic signal

⇒ Multi-messenger approach

Dark Sirens

GWs event are associated to a potential host galaxy from which z is inferred

⇒ Multi-tracer approach

Spectral Sirens

Features in spectrum of the GWs population pinpoint the source z

⇒ Statistical approach

Using cross-correlation as independent approach



Standard Approach: GW x Galaxy Surveys

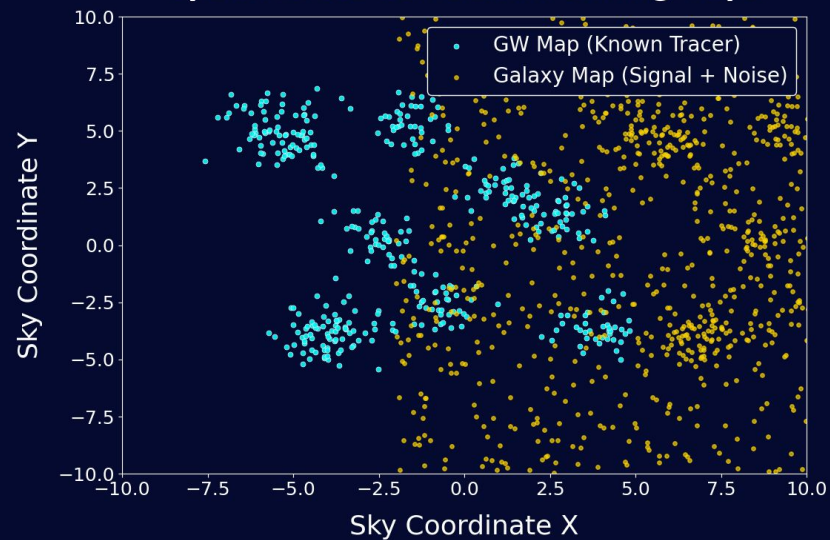
→ **Fundamental assumption:**

Both GW sources and galaxy population follow the same underlying DM distribution

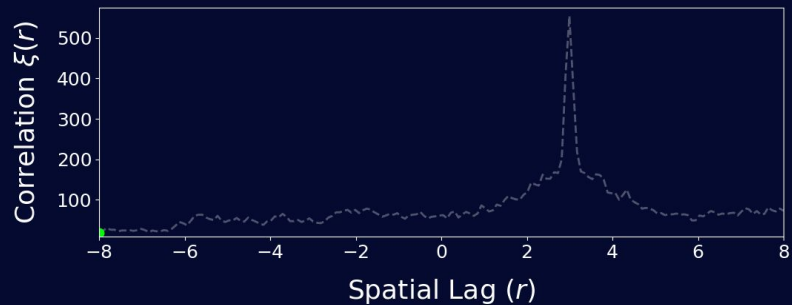
- **Galaxy Surveys:**
Clustering statistics in redshift space;
- **GWs:**
Clustering statistics in luminosity distance space

Cross-correlation in a multi-tracer perspective to unlock cosmological information

Spatial Cross-Correlation: Sliding Maps



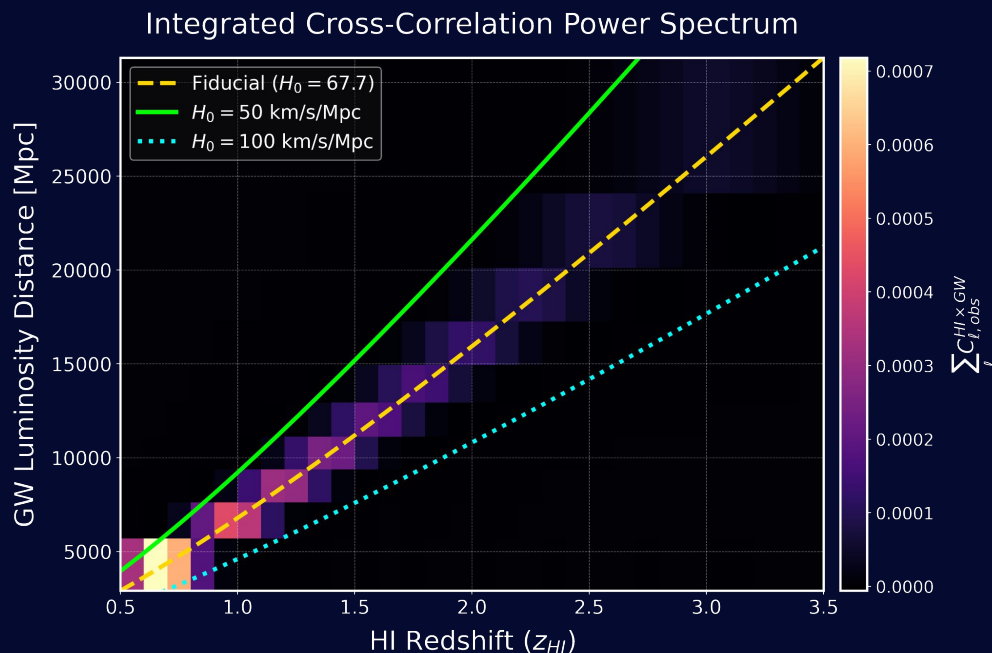
Cross-Correlation Amplitude



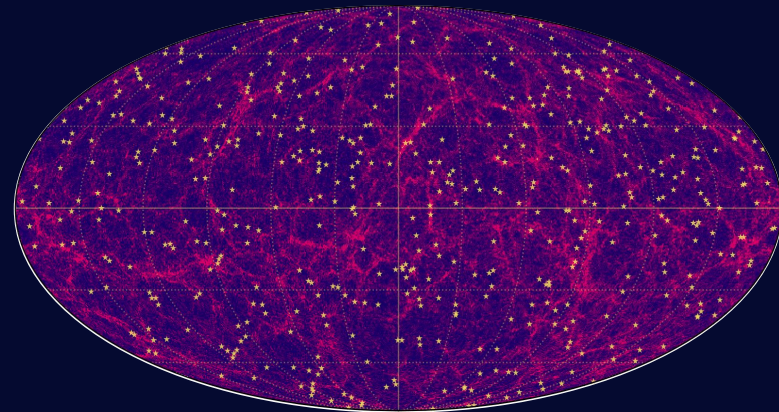
Cross-Correlation: Key point of the approach

Access to properties of **two different** tracers of the **same underlying** density field in **two different spaces**

Combination of data requires the conversion between z and d_L : Cross-correlation is maximised when the **correct distance-redshift relation** is adopted



Using neutral hydrogen intensity mapping as LSS tracer



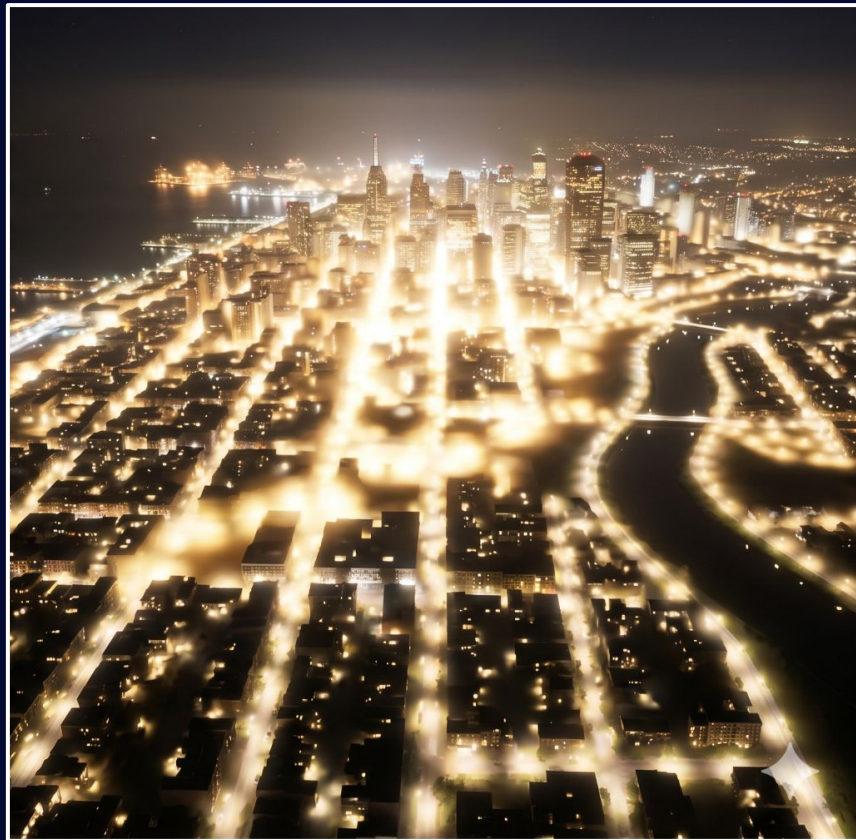
Galaxy Catalogues

Measuring and resolve
individual sources



Intensity Mapping

Measures the cumulative,
collective light coming from
a broad region of space



Why is HI interesting?

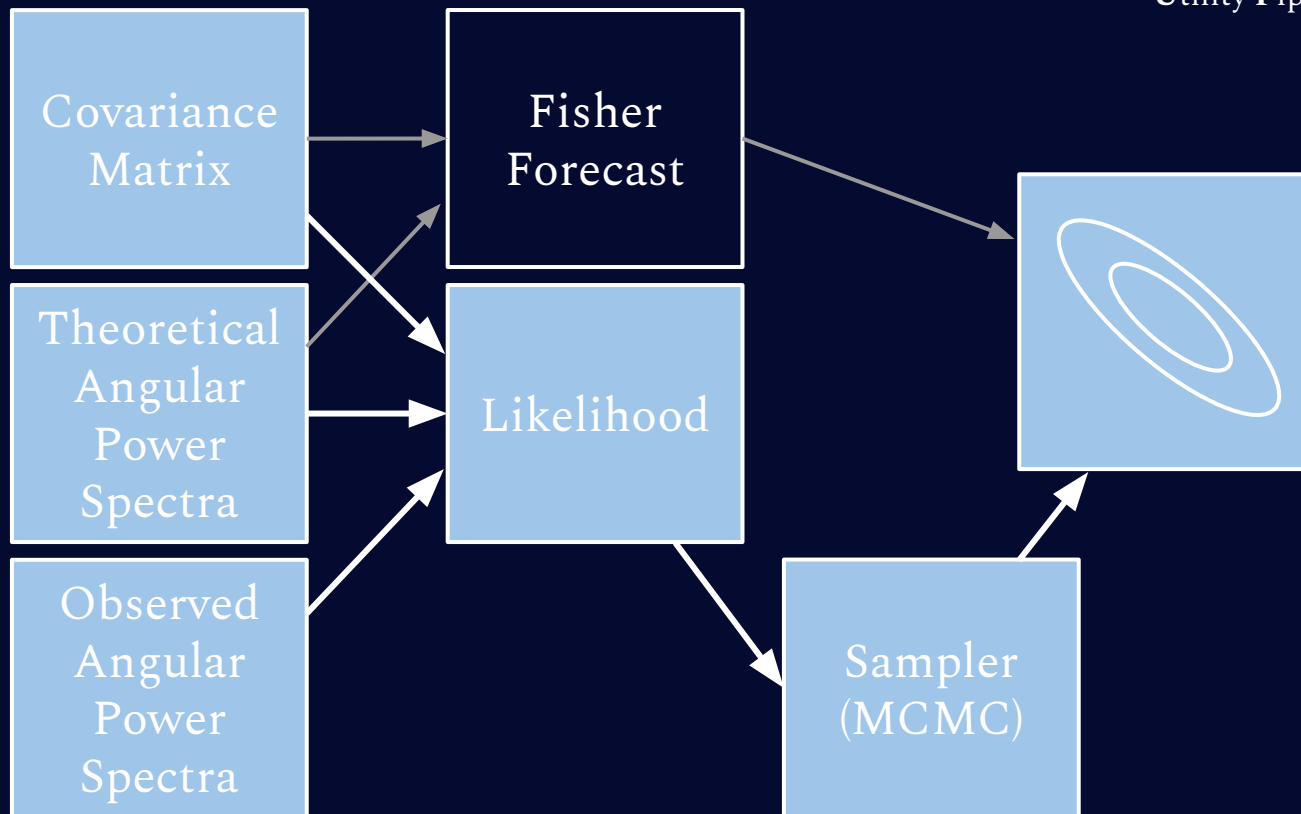
- 1) Covers large cosmological volumes with respect to resolved galaxy surveys, in fast and inexpensive way;
- 2) Spectroscopic precision in redshift distribution up to $z \lesssim 5$;
- 3) Precise measurement of matter abundance thanks to intensity of the line;
- 4) Upcoming future observatory (SKA Observatory)

Likelihood Formalism

GWHICcUP:

GW x HI Cross-correlation

Utility Pipeline



Likelihood Formalism

Likelihood

$$\ln \mathcal{L}(\Lambda) = -\frac{1}{2} \sum_{ij} \sum_{i'j'} \sum_{\ell\ell'} \left(\tilde{C}_{\ell}^{ij} - C_{\ell}^{th,ij}(\Lambda) \right)^T \mathcal{C}_{\ell\ell'}^{-1} \left(\tilde{C}_{\ell'}^{i'j'} - C_{\ell'}^{th,i'j'}(\Lambda) \right)$$

Covariance
Matrix

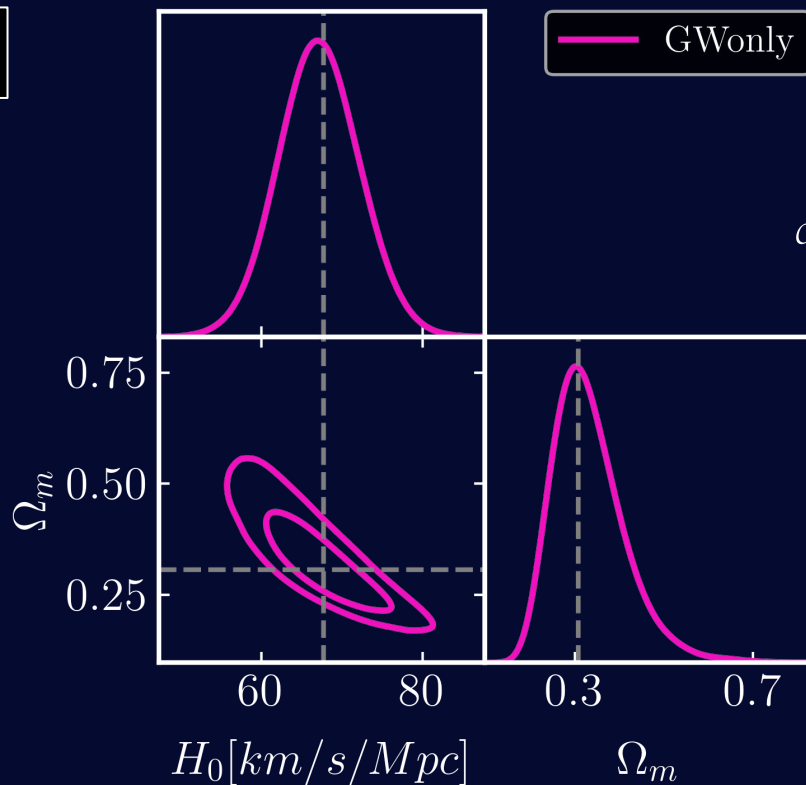
Full Matrix

$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} \text{HIxHI} & & \\ \boxed{(HIHI_{\ell}, HIHI_{\ell'})} & (HIHI_{\ell}, GWHI_{\ell'}) & (HIHI_{\ell}, GWGW_{\ell'}) \\ & \text{GWxHI} & \\ (GWHI_{\ell}, HIHI_{\ell'}) & \boxed{(GWHI_{\ell}, GWHI_{\ell'})} & (GWHI_{\ell}, GWGW_{\ell'}) \\ & & \text{GWxGW} \\ (GWGW_{\ell}, HIHI_{\ell'}) & (GWGW_{\ell}, GWHI_{\ell'}) & \boxed{(GWGW_{\ell}, GWGW_{\ell'})} \end{bmatrix}$$

$$(AB_{\ell}, CD_{\ell'}) = Cov[C_{\ell}^{AB}, C_{\ell'}^{CD}] = \frac{\delta_{\ell\ell'}}{(2\ell+1)f_{fov}} \left[C_{\ell}^{A_i B_k} C_{\ell'}^{B_j D_n} + C_{\ell}^{A_i D_n} C_{\ell'}^{B_j C_k} \right]$$

Results: GWxGW

ET2L+CE



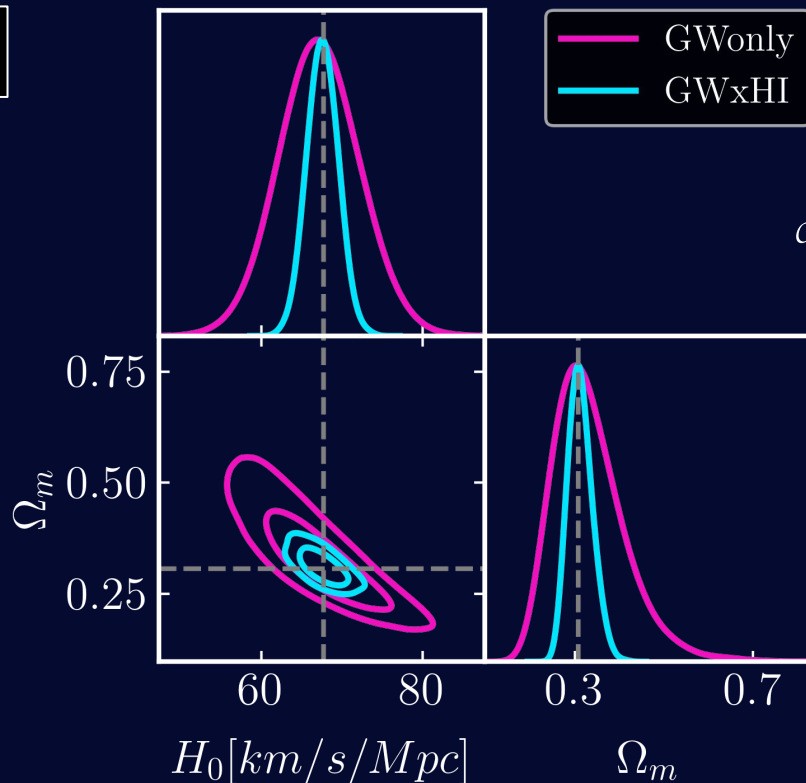
$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & \boxed{(GWGW_\ell, GWGW_{\ell'})} \end{bmatrix}$$

GWxGW

[<https://arxiv.org/abs/2607.26193>]

Results: GWxGW + Cross-Correlation

ET2L+CE

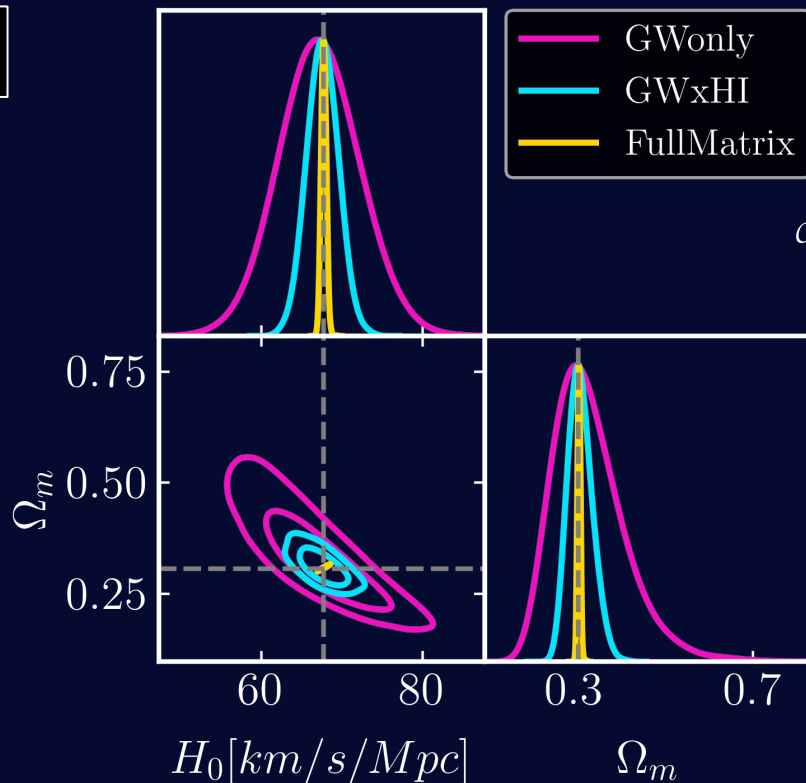


$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (H_0 H_0, H_0 H_0) & (H_0 H_0, GWHI) & (H_0 H_0, GWGW) \\ (GWHI, H_0 H_0) & \text{GWxHI} & (GWHI, GWGW) \\ (GWGW, H_0 H_0) & (GWGW, GWHI) & \text{GWxGW} \end{bmatrix}$$

[<https://arxiv.org/abs/2607.26193>]

Results: Full Analysis

ET2L+CE

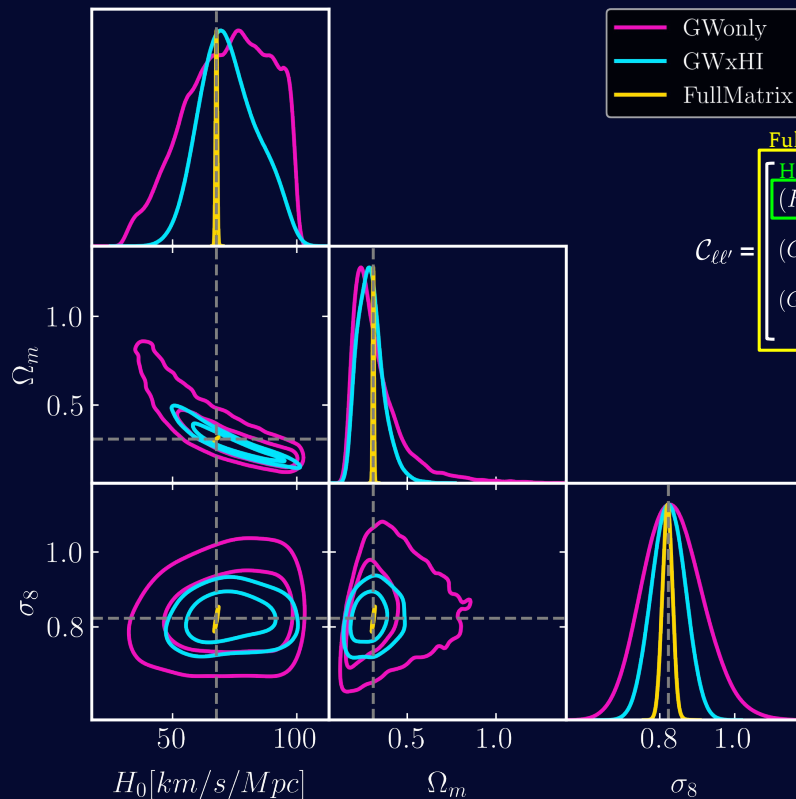


$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} \text{HIxHI} & & \\ (HIHI_{\ell}, HIHI_{\ell'}) & (HIHI_{\ell}, GWHI_{\ell'}) & (HIHI_{\ell}, GWGW_{\ell'}) \\ & \text{GWxHI} & \\ (GWHI_{\ell}, HIHI_{\ell'}) & (GWHI_{\ell}, GWHI_{\ell'}) & (GWHI_{\ell}, GWGW_{\ell'}) \\ & & \text{GWxGW} \\ (GWGW_{\ell}, HIHI_{\ell'}) & (GWGW_{\ell}, GWHI_{\ell'}) & (GWGW_{\ell}, GWGW_{\ell'}) \end{bmatrix}$$

[<https://arxiv.org/abs/2607.26193>]

Results: Extended Run

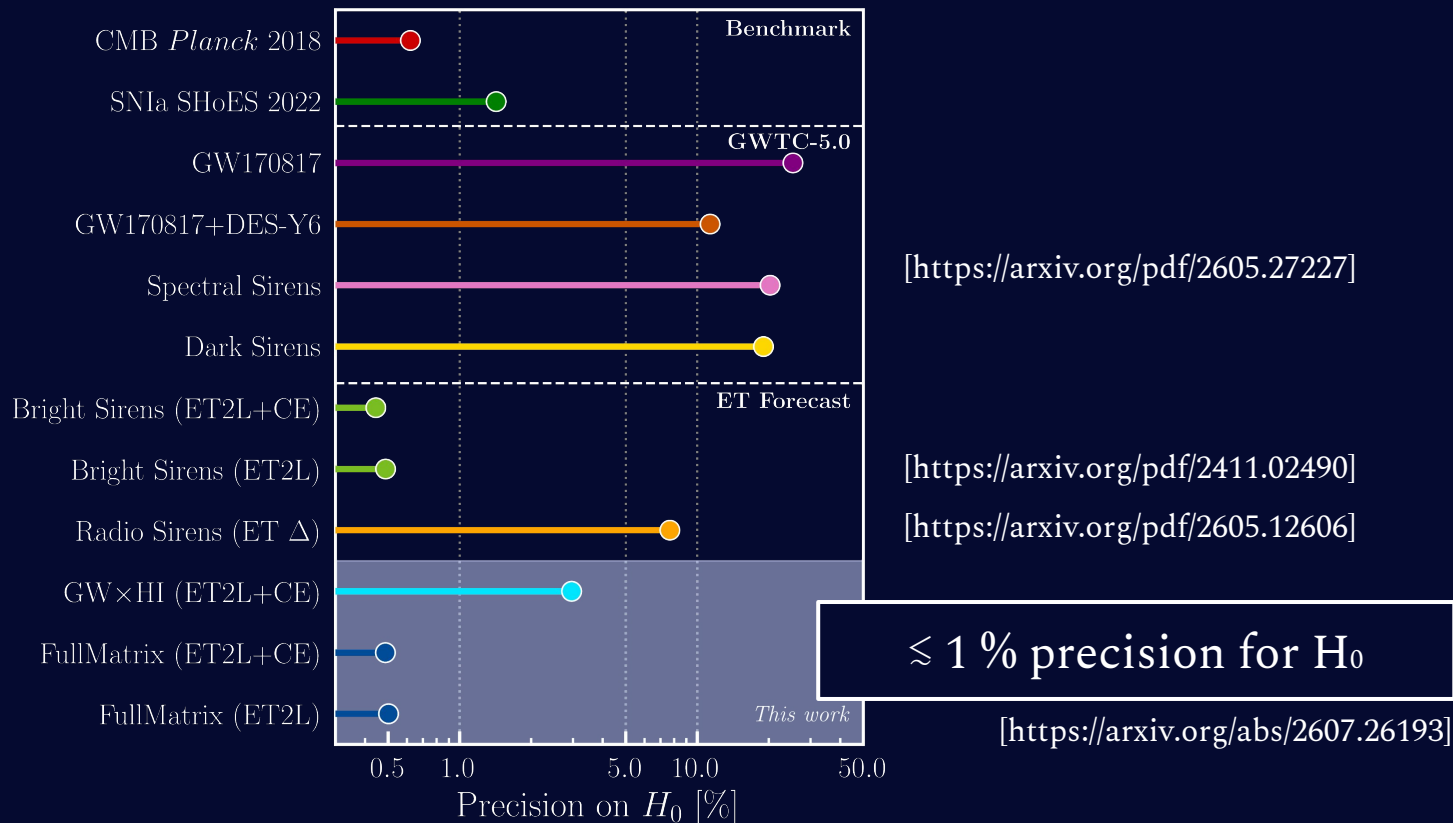
ET2L+CE



$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} \text{Full Matrix} & & \\ \text{HIxHI} & & \\ (HIHI_{\ell}, HIHI_{\ell'}) & (HIHI_{\ell}, GWHI_{\ell'}) & (HIHI_{\ell}, GWGW_{\ell'}) \\ \text{GWxHI} & & \\ (GWHI_{\ell}, HIHI_{\ell'}) & (GWHI_{\ell}, GWHI_{\ell'}) & (GWHI_{\ell}, GWGW_{\ell'}) \\ \text{GWxGW} & & \\ (GWGW_{\ell}, HIHI_{\ell'}) & (GWGW_{\ell}, GWHI_{\ell'}) & (GWGW_{\ell}, GWGW_{\ell'}) \end{bmatrix}$$

[<https://arxiv.org/abs/2607.26193>]

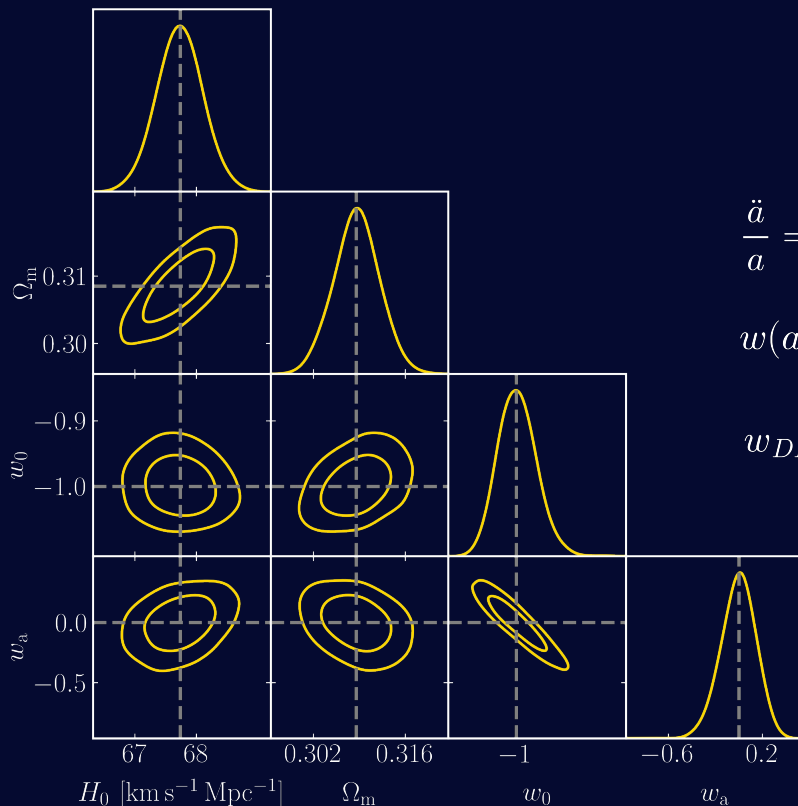
Results: Constraints on H_0



Beyond Standard Cosmological Model

ET2L+CE

Extend the analysis to
beyond the standard
cosmological
framework to test Dark
Energy models

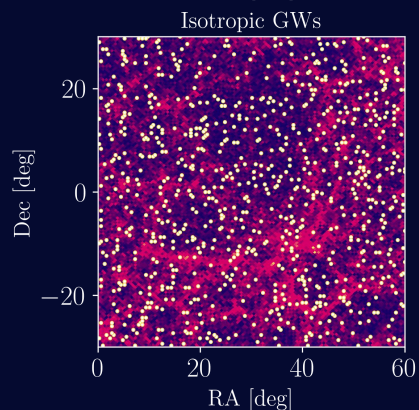
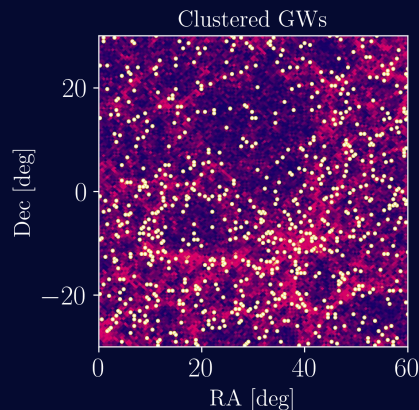
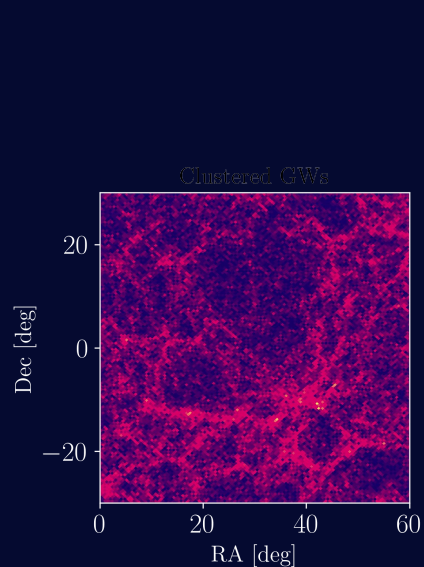
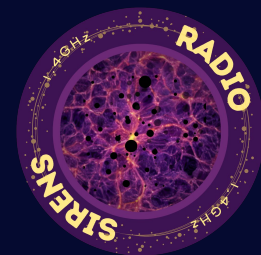


$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}[\rho_m + \rho_{DE}(1 + 3w(a))]$$

$$w(a) = \frac{p(a)}{\rho(a)}$$

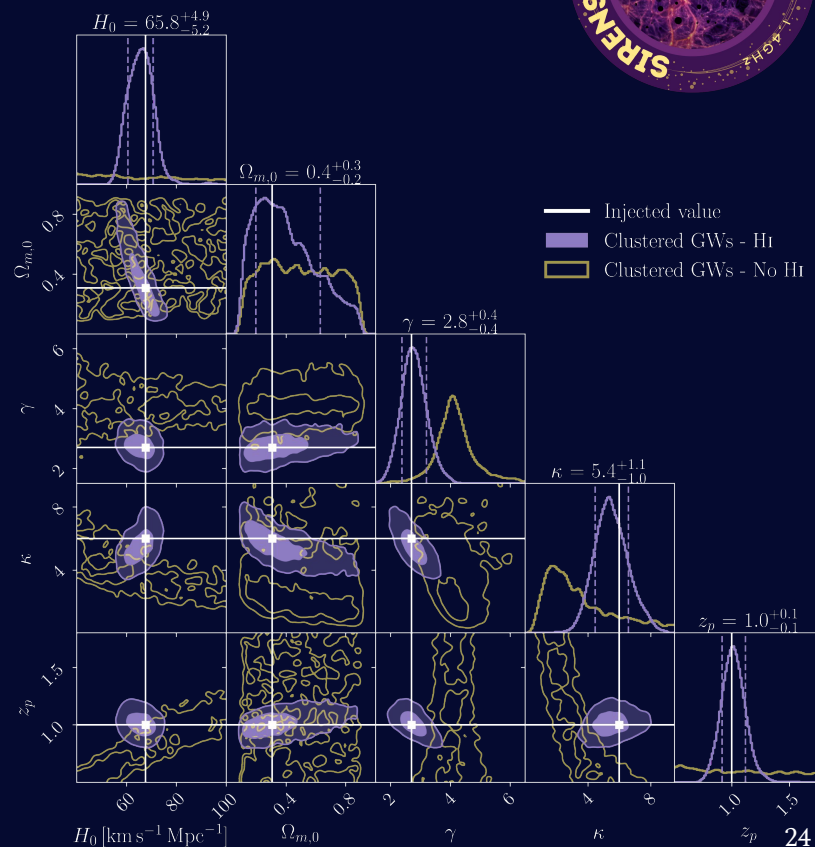
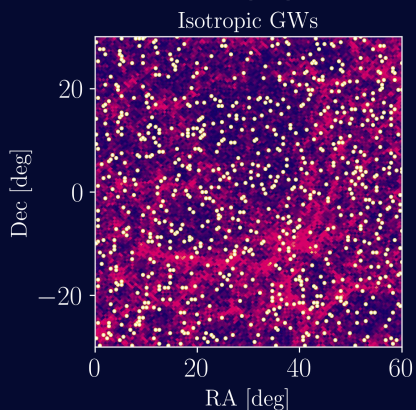
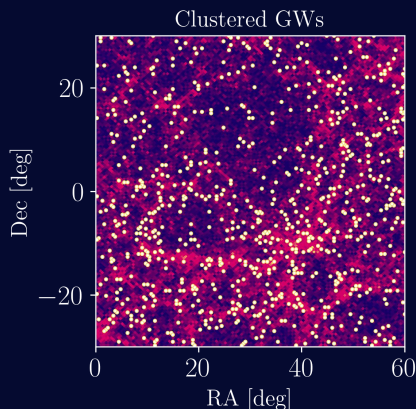
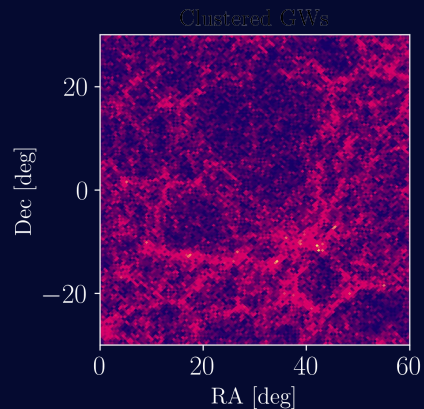
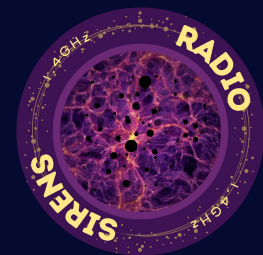
$$w_{DE}(a) = w_0 + w_a(1 - a)$$

Extending to Population Properties



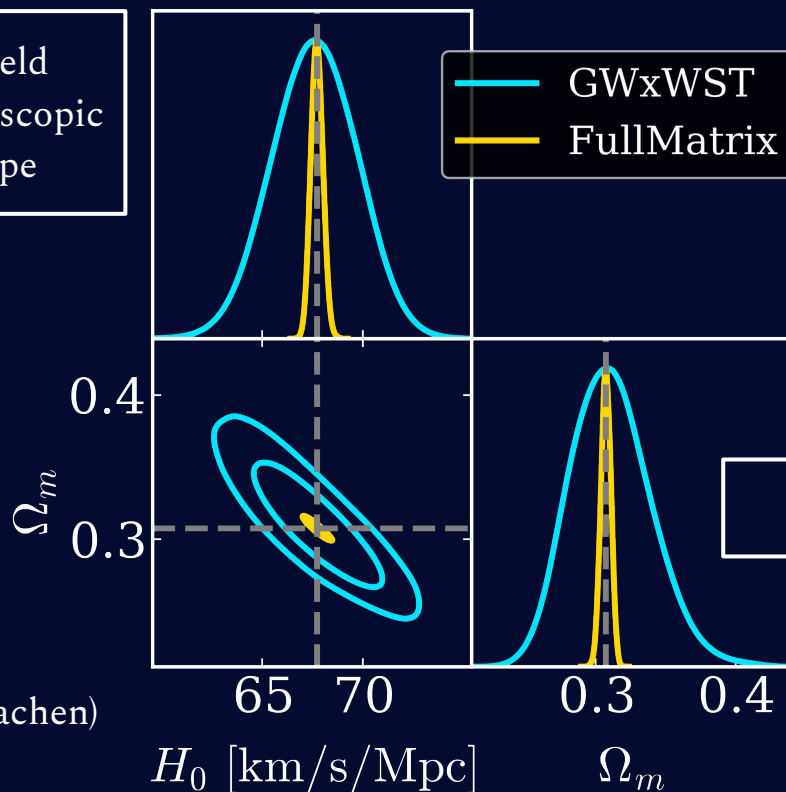
Credit: U. Dupletsa
<https://arxiv.org/pdf/2605.12606>

Extending to Population Properties



Credit: U. Dupletsa
<https://arxiv.org/pdf/2605.12606>

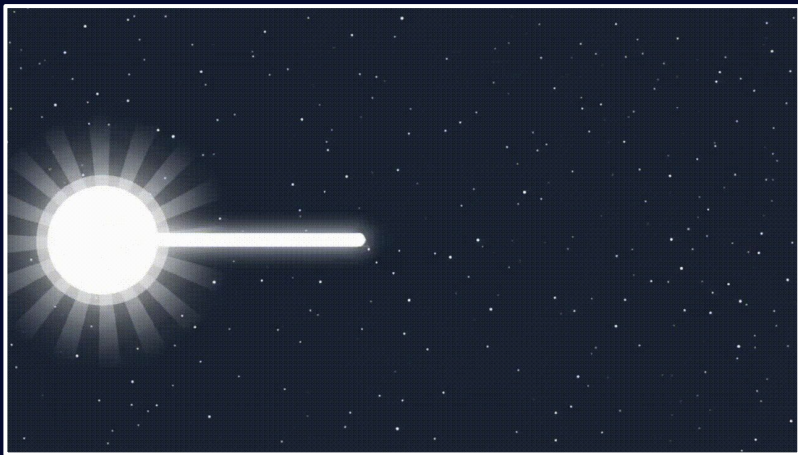
Next steps: Spectroscopic Galaxy Catalogs



PRELIMINARY

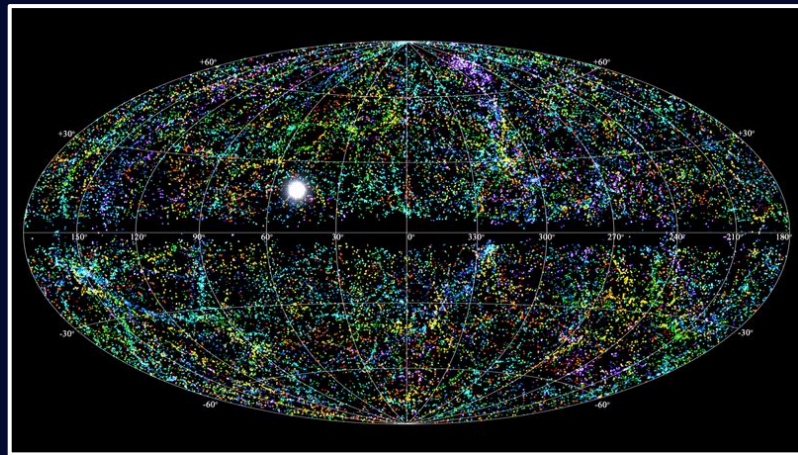
In collaboration
with G. Sala (RWTH Aachen)

Future Developments: Alternative Tracers



Lyman- α forest

(In collaboration with M. Viel, G. Scelfo; SISSA)



Fast Radio Bursts

(In collaboration with M. Pili; UniCA)

Papers:

- **Schulz M.**, et al.; *Cosmology with cross-correlation of gravitational waves and 21 cm intensity mapping in view of ET and SKAO*. [submitted to JCAP];
- Tissino J, et al. incl. **Schulz M.**; *Sky localization with gravitational-wave detector networks: eliminating a hidden coordinate dependence*. [submitted and accepted for publication at npj Space Exploration];
- Dupletsa U., et al. incl. **Schulz M.**; *Radio Sirens: measuring the Expansion History with the SKA Observatory and the Einstein Telescope* [submitted to MNRAS];
- various LVK Collaboration papers, incl. **Schulz M.**

3rd Year Outreach Activities:

- **Periferie Creative**: Spring 2026, L'Aquila;
- **High School Mentoring**: March 2026, L'Aquila;
- **Stelle e Spazio**: June 2026, L'Aquila;
- **IDeAS4Students**: July 2026, Sardinia;
- **SHARPER**: September 2026, L'Aquila.

3rd Year Conference & Workshops:

- **Young Researcher Meeting**: October 2025, L'Aquila;
- **ET Annual Meeting**: November 2025, Opatija, Croatia;
- **Progress on Old and new Themes in cosmology (PONT)**: April 2026, Avignon, France;
- **Universum VII**: May 2026, Naples;
- **SGWS workshop**: May 2026, Cagliari;
- **XVI ET Symposium**: June 2026, Aachen, Germany;
- **Invited talk @ RWTH**: June 2026, Aachen, Germany.

The work is carried out with the support from the Sardinian GW Science (SGWS) Community: a joint program between the University of Cagliari and GSSI promoted and coordinated by the cultural association IDeAS

Extra slides

Distribution and Accessibility



GWHICcUP: Gravitational Wave x neutral
hydrogen (HI) Cross-correlation Utility Pipeline



MultiCLASS



Montepython

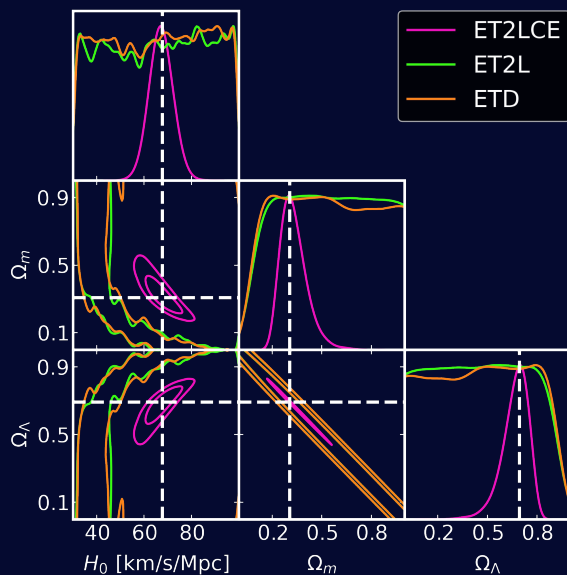


Cobaya

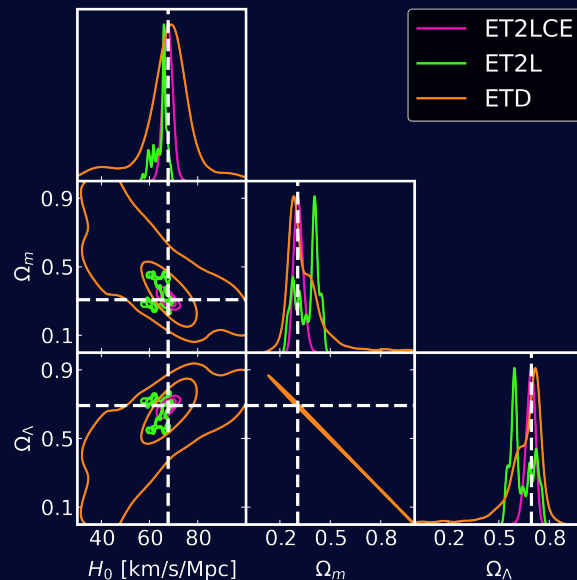
Detector Setup



Detector Performance



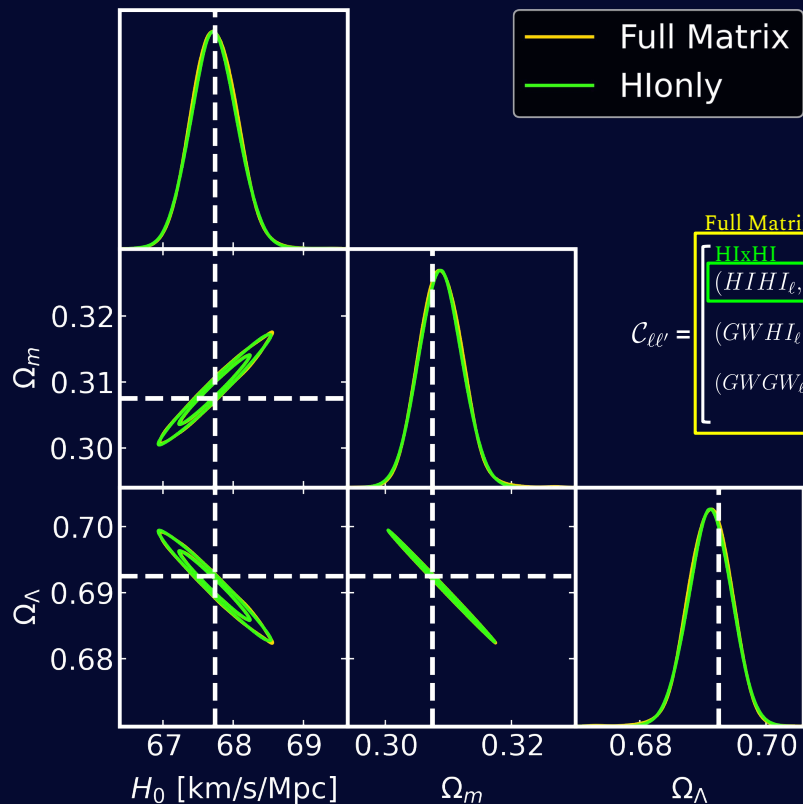
$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$



$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

HIxHI

ET2L+CE



$$\mathcal{C}_{\ell\ell'} = \begin{bmatrix} \text{HIxHI} & & \\ (HIHI_\ell, HIHI_{\ell'}) & (HIHI_\ell, GWHI_{\ell'}) & (HIHI_\ell, GWGW_{\ell'}) \\ (GWHI_\ell, HIHI_{\ell'}) & (GWHI_\ell, GWHI_{\ell'}) & (GWHI_\ell, GWGW_{\ell'}) \\ (GWGW_\ell, HIHI_{\ell'}) & (GWGW_\ell, GWHI_{\ell'}) & (GWGW_\ell, GWGW_{\ell'}) \end{bmatrix}$$

[Schulz et al., in preparation]

Angular Power Spectrum Formalism

Computing tomographic
cross-correlation by looking at the
angular power spectrum: C_ℓ

→ advantage of naturally including effects
coming from large angular separations,
which are closely tied to cosmology and
its evolution

$$\delta^X(\theta, \phi, x) = \frac{\rho^X(\theta, \phi, x) - \langle \rho^X \rangle(x)}{\langle \rho^X \rangle(x)}$$

$$\delta^X(\theta, \phi, x) = \sum_{\ell=0}^{+\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^X(x) Y_{\ell m}(\theta, \phi)$$

$$C_\ell^X(x) = \langle a_{\ell m}^X(x)^2 \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^X(x)^2$$

Likelihood Formalism and Evaluation

Theoretical
Angular
Power
Spectra

$$C_l^{XY}(x_i, x_j) = \int_{z_{min}}^{z_{max}} \frac{cdz}{H(z)r^2(z)} \tilde{W}^X(z, x_i) \tilde{W}^Y(z, x_j) P\left(\frac{\ell + 1/2}{r(z)}, z\right)$$

$$\tilde{W}^X(z, x_i) = J_X(z) b_X(z) w^X(z, x_i) \frac{H(z)}{c} \quad w^X(x, x_i) = W^X(x, x_i) \frac{dN_{obs}^X}{dx} \frac{1}{\int dx' W^X(x', x_i) \frac{dN_{obs}^X}{dx'}}$$

Covariance
Matrix

$$C_\ell = (C_\ell^{XX}(x_1, x_{,1}), C_\ell^{XX}(x_1, x_{,2}), \dots, C_\ell^{XX}(x_n, x_{,n}), C_\ell^{XY}(x_1, x_{,1}), \dots, C_\ell^{XY}(x_n, x_{,m}), C_\ell^{YY}(x_1, x_{,1}), \dots, C_\ell^{YY}(x_m, x_{,m}))^T$$

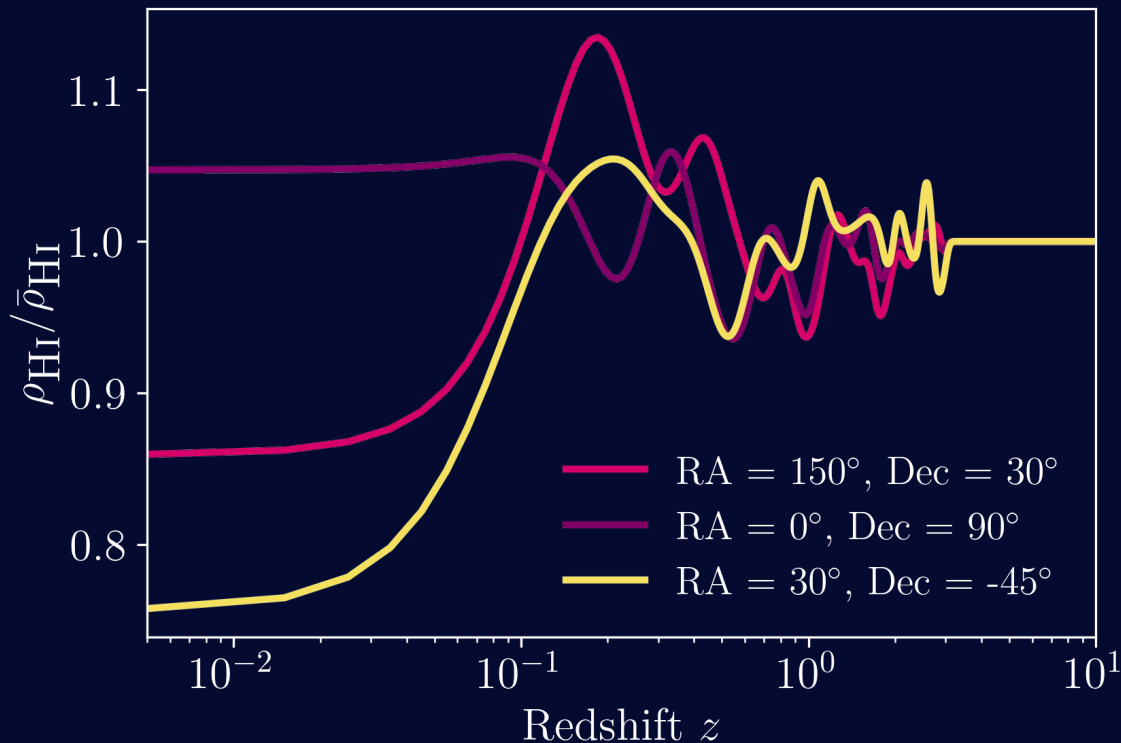
$$[Cov(\ell)]_{IJ} = C_\ell^{I_1 J_1} C_\ell^{I_2 J_2} + C_\ell^{I_1 J_2} C_\ell^{I_2 J_1}$$

Likelihood

$$\ln \mathcal{L}(\Lambda) = \frac{1}{2} \sum_{ij} \sum_{i'j'} \sum_{\ell\ell'} \left(\tilde{C}_\ell^{ij} - C_\ell^{th,ij}(\Lambda) \right) [Cov_{\ell\ell'}]^{-1} \left(\tilde{C}_{\ell'}^{i'j'} - C_{\ell'}^{th,i'j'}(\Lambda) \right)$$

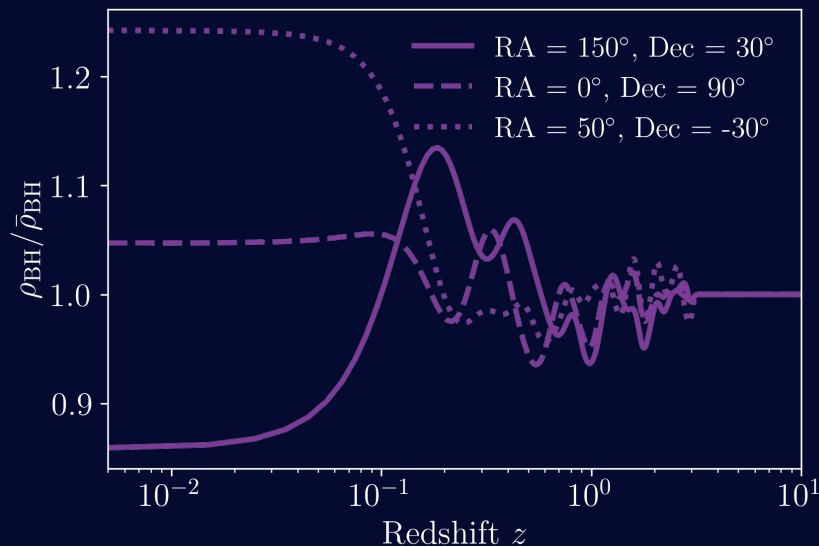
Observations of HI: line-of-sight redshift prior

Mock HI
maps
SKA-Mid-like



Mock GW data

Mock BBHs
ET-like
detections



Parametrize the CBC merger rate as a function of density contrast of HI maps

$$\frac{dN_{CBC}}{dzdt d\Omega} = \frac{dN_{CBC}}{dM_{BH} dt_{src}} \frac{1}{1+z} \frac{dM_{BH}}{dz d\Omega}$$

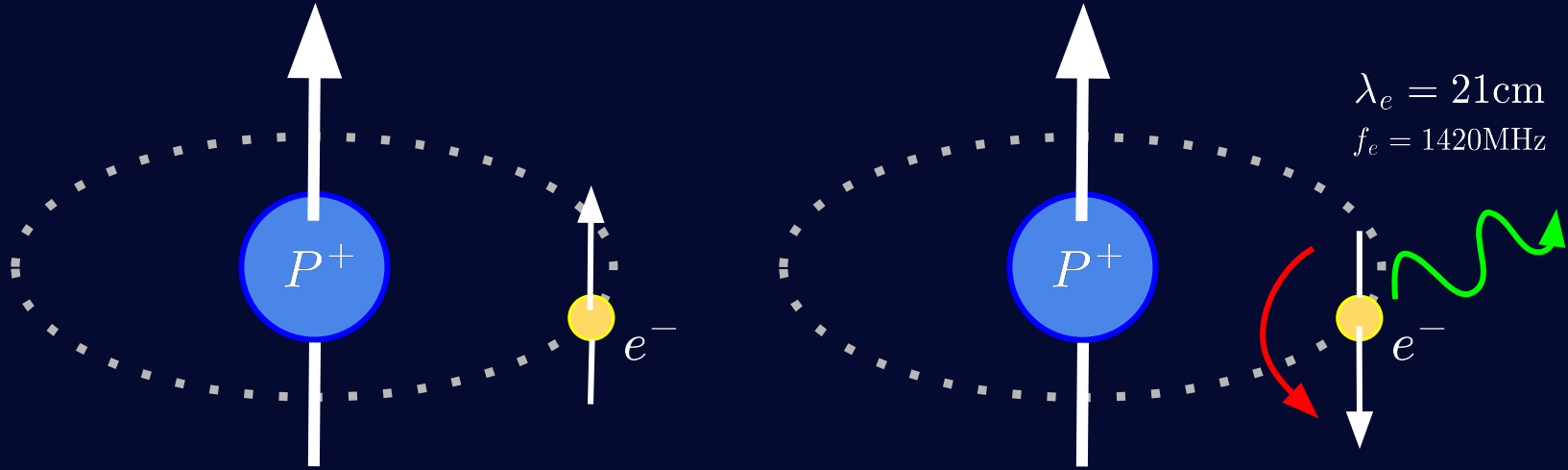
$$\begin{aligned} \frac{dN_{CBC}}{dM_{BH} dt_{src}} &= R_{BH} \psi(z|\gamma, \kappa, z_p) \\ &= R_{BH} [1 + (1+z_p)^{-\gamma-\kappa}] \frac{(1+z)^\gamma}{1 + \left[\frac{1+z}{1+z_p}\right]^{\gamma+\kappa}} \end{aligned}$$

[Madau-Dickinson 2014]

$$\frac{dM_{BH}}{dz d\Omega} = \frac{dM_{BH}}{dV_c} \frac{dV_c}{dz d\omega} = \rho_{BH}(z, \Omega) \frac{dV_c}{dz d\omega}$$

$$\rho_{BH}(z, \Omega) = \bar{\rho}_{BH} [1 + b_{GW} (1+z)^{\alpha_{GW}} \delta_{DM}(z, \Omega)]$$

Neutral Hydrogen



Neutral Hydrogen post Reionization

Post Reionization $z \lesssim 5$ the
Universe is mostly ionized

- IGM is ionized $\rightarrow$ no emission of 21 cm;
- HI is “locked” inside galactic environments,
i.e. inside dark matter halos
- HI distribution maps the dark matter distribution